

214 * GPS-Aided Gravimetry at 30 Km Altitude from a Balloon-Borne Platform 47

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ABSTRACT

A balloon-borne experiment, flown at 30 Km altitude over New Mexico, was used to test dynamic differential GPS tracking in support of gravimetry at high-altitudes. The experiment package contained a gravimeter (Vibrating String Accelerometer), a full complement of inertial instruments, a TI-4100 GPS receiver and a radar transponder. The flight was supported by two GPS receivers on the ground near the flight path. From the 8 hour flight, about a forty minute period was selected for analysis. Differential GPS phase measurements were used to estimate changes in position over the sample time interval, or average velocity. In addition to average velocity, differential positions and numerical averages of acceleration were obtained in three components. Gravitational acceleration was estimated by correcting for accelerations due to translational motion, ignoring all rotational effects.

INTRODUCTION

The primary objective of this flight (named DUCKY II, flown in October 1985) was to test the differential GPS tracking system; the secondary objective was to improve on the gravity field measurement shown to be feasible with the previous flight (named DUCKY Ia, flown in October 1983). As with DUCKY Ia, a great deal of data were collected, organized, inspected and analyzed by several different groups. Overall, the flight, data collection and analysis went very well, but a few problems did complicate the data analysis sufficiently that the full promise of this experiment was not fulfilled. Nevertheless, we did succeed in demonstrating GPS tracking and improving the quality of the gravity measurements from DUCKY Ia.

TEST DESCRIPTION

The principal limitation in high-altitude gravimetry, as concluded from the flight of DUCKY Ia, is high accuracy tracking. Since all accelerometers measure only acceleration and cannot distinguish between gravitational acceleration and kinematic acceleration, it is critical to add sensors to aid in separating the two. There are only two known ways in which this can be done: 1) External tracking to directly determine kinematic acceleration; or 2) Gravity gradiometry to directly detect gravitational acceleration. External tracking works by measuring position, velocity and acceleration relative to the tracking device, which is fixed, usually in a non-inertial frame. We chose external tracking via GPS because it is a lot simpler, and it has the potential to resolve a few mGal accelerations with available technology. DUCKY II did have inertial sensors, and when properly combined with GPS, highly accurate tracking data is possible.

GPS tracking for DUCKY II was accomplished using three DMA versions of the TI 4100 receivers. One in flight and two on the ground. The two ground stations were picked to minimize distance between ground receiver and balloon. For the flight, one ground station was placed at AFGL Det. 1, near the launch site; and the other was placed on the roof of the Post Office in Lovington, NM, near the expected landing area. The data from the flight

receiver was telemetered and analyzed in real-time, just as the ground stations; only the hard line was replaced with a radio link.

At the time of flight, GPS was a pilot program, with only six satellites in orbit. GPS will not be a mature service until at least the late 1980's or early 1990's. When GPS is fully operational, this experiment could be repeated, with good satellite coverage and geometry, from launch to landing. As GPS time was limited, we intended to put the best coverage at altitude; future flights will cover the ascent - a time of high interest. The ascent time covers 25 to 30 Km of vertical distance, and gravitational acceleration and gradient data would be most interesting. Currently, we have demonstrated that this system works.

GPS DATA PROCESSING

The data processing is shown diagrammatically in Figure 1. First, a rough estimate of absolute position was obtained using a Kalman Filter with pseudorange measurements. Next, the combined L₁ and L₂ frequency pseudorange measurements and change in range from phase measurements were combined to obtain an average estimate of the pseudorange at the first data time. Here, change in range Doppler measurements were subtracted from succeeding pseudoranges for the entire satellite pass and averaged to obtain a more accurate estimate of the pseudorange at the initial start GPS solution time. Next, the pseudorange values were used to obtain the initial number of wavelengths between double differenced phase measurements. The double-differenced phase measurements were obtained by first differencing between the two receivers. Then, the phase measurements were differenced between two satellites, where for this set of data PRN 11 was the reference satellite. Using data from four satellites (PRNs 6, 9, 11 and 12), the relative position of the balloon was obtained at each 6 second time mark. This relative positioning procedure corrects the absolute positioning estimates, discussed above.

The average velocity was determined next using only the very accurate L₁ change in phase measurements. The standard Doppler procedure was used to obtain change in range values. Using the relative positioning values obtained above for the correction partials, average position changes were estimated over each data interval. Finally, the accelerations, most importantly the vertical accelerations, were obtained using a basic numerical difference between successive average velocity values divided by the time interval. These accelerations represent the acceleration due to all forces and are represented in the geodetic coordinate frame.

TEST RESULTS

GPS estimates of vertical acceleration were first obtained between the two static receivers at Holloman and Lovington sites. Here, the Doppler procedure for obtaining average velocity over a 6 sec interval was used and numerically differentiated to obtain vertical acceleration. Here, the estimates had a numerical standard deviation of 39.3 mGals. When averaged over the 15 minute interval of data available to the two sites (and the balloon) an error of only 0.087 mGals was obtained. Even though the receivers were in a low noise static mode rather than a slightly higher noise low dynamic mode, this is still a very good indication that GPS is sufficiently precise to obtain accurate gravity estimates.

The GPS data was then processed for the balloon with respect to both static sites. However, since Holloman had such a small amount of simultaneous data with the balloon, only the results of the balloon with

respect to Lovington are presented. The data was processed as described above. The relative vertical position as a function of time is presented in Figure 2. During this time period, the balloon moved with average velocities of about 9 m/s in the North direction and about 17.5 m/s in the East direction. The cyclic vertical motion was due to gas in the balloon expanding and contracting as the balloon changed altitude and correspondingly temperature. Doppler estimates of vertical velocity were obtained and numerically differentiated to produce the vertical acceleration given in Figure 3. This can be compared with the Vibrating String Accelerometer (VSA) measurements given in Figure 4.

In order to obtain a gravity value, the 30 km altitude of the balloon trajectory, modeled gravity as a function of height was obtained and removed from the GPS accelerations. Also, Eotvos and Earth rotation corrections were made. A constant value was found for the difference between the corrected GPS accelerations and the raw accelerometer measurements. The value obtained was 90 mGal. This value, if all computations were done correctly, should theoretically be due to the difference between the modeled gravity and actual gravity at a 30 km altitude. However, there appears to be a bias that has not been accounted for.

SUMMARY

The two flights completed in this program have demonstrated that gravimetry is possible at 30 Km altitudes. Although the original goal of 1 mGal accuracy has not been reached, much has been learned from the test. The key is GPS differential tracking, which has been demonstrated with this flight. The results of the static GPS acceleration estimates indicate that GPS has sufficient accuracy to obtain satisfactory acceleration estimates. However, the results of the dynamic high altitude portion of the test indicate that a bias is in the data. With the information available from the test, it has been difficult to isolate this bias. That is, the bias could be in the gravimeter, the gravity model, or computational corrections. It is recommended that further testing be performed in a controlled manner close or on the Earth's surface to further validate the accuracy of the GPS/gravimeter procedure. As the GPS constellation increases in number, this work will become much easier in planning and scheduling flights. If and when the next flight occurs, we should have good tracking throughout the ascent and flight; certainly that dataset would be unique as the only vertical profile over 30 Km.

ACKNOWLEDGEMENTS

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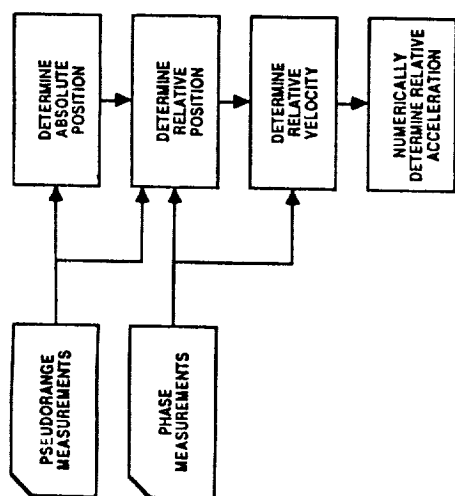


Fig. 1. Flow diagram for GPS data for analysis of acceleration.

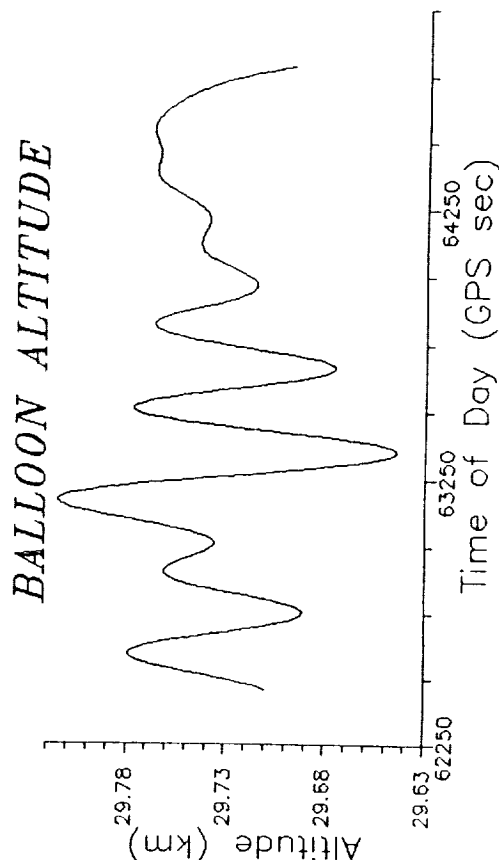


Fig. 2. Balloon altitude from GPS differences with Lovington, NM.

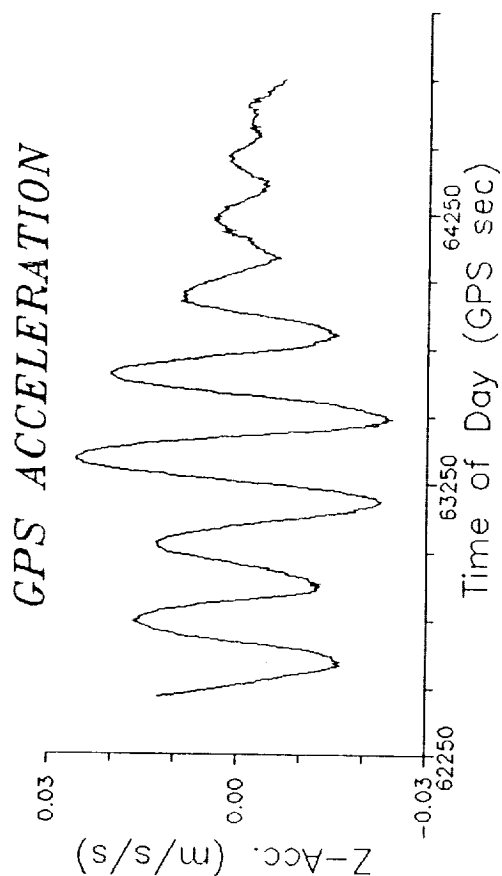


Fig. 3. Balloon Z-acceleration from GPS differences with Lovington.

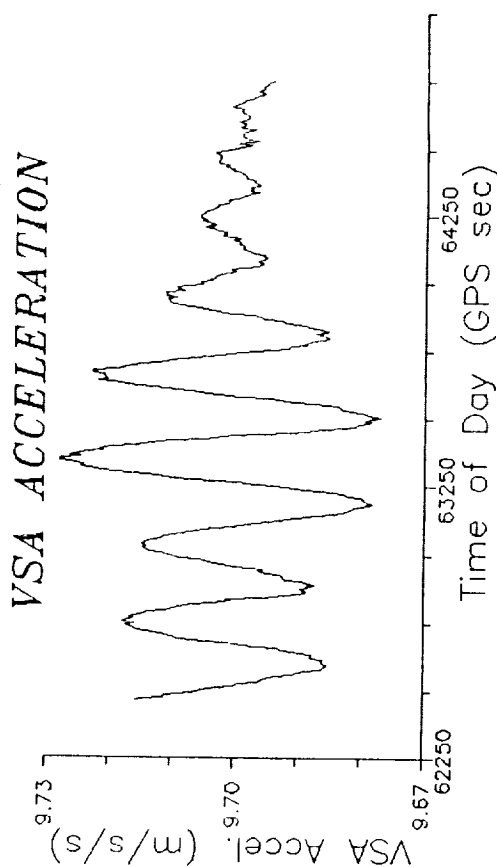


Figure 4. Balloon Z-acceleration as directly measured by the gravimeter.